Brachial Plexus Injury: A Survey of 100 Consecutive Cases from a Single Service

Annie S. Dubuisson, M.D.
Department of Neurosurgery, Centre Hospitalier Universitaire de Liège, Domaine Universitaire du Sart Tilman, Liège, Belgium

David G. Kline, M.D.
Department of Neurosurgery, Louisiana State University Medical Center, and Charity, University, and Ochsner Hospitals, New Orleans, Louisiana

Reprint requests:
Annie S. Dubuisson, Department of Neurosurgery, Centre Hospitalier Universitaire de Liège, Domaine Universitaire du Sart Tilman, Bâtiment B 35, B-4000 Liège, Belgium.
Email: A.Dubuisson@chu.ulg.ac.be

Received, December 10, 2001.
Accepted, January 30, 2002.

OBJECTIVE: We analyzed the epidemiology, preoperative management, operative findings, operative treatment, and postoperative results in a group of 99 patients who sustained 100 injuries to the brachial plexus.

METHODS: The charts of 100 consecutive surgical patients with brachial plexus injuries were reviewed.

RESULTS: The patient group comprised 80 males and 19 females ranging from 5 to 70 years of age. One male patient had bilateral brachial plexus palsy. Causes of injury were largely sudden displacement of head, neck, and shoulder and included 27 motorcycle accidents. There were 23 open wounds, including 8 gunshot wounds, 6 other penetrating wounds, and 9 wounds caused by operative or iatrogenic trauma. Loss was exhibited at C5–C6 in 19 patients, at C5–C7 in 15 patients, and at C5–T1 in 39 patients, and 8 patients had another spinal root pattern of injury. Nineteen patients had injury at the cord or the cord to nerve level. Associated major trauma was present in 59 patients. Emergency surgery for vessel or nerve repair was necessary in 18 patients. Myelography (n = 57) or magnetic resonance imaging (n = 7) revealed at least one root abnormality in 52 patients. The median interval from trauma to operation was 7 months. Operative exposures used included anterior supraclavicular, infraclavicular, combined supra- and infraclavicular, or a posterior approach in 5, 14, 77, and 4 patients, respectively. The surgical procedures performed included neurolysis alone in 12 patients and nerve grafting, end-to-end anastomosis, and/or neurotization in 81, 5, and 47 patients, respectively. Postoperative follow-up of at least 36 months was conducted in 78% of the patients. *Grade 3 recovery* according to Louisiana State University Medical Center criteria means contraction of proximal muscles against some resistance and of distal muscles against at least gravity. Among the 18 patients with open wounds, 14 (78%) recovered to a Grade 3 or better level, as did 35 (58%) of 60 patients with stretch injuries. In all cases of C5–C6 stretch injuries repaired by nerve grafting (n = 10), the patients recovered useful arm function.

CONCLUSION: Brachial plexus injury represents a severe, difficult-to-handle traumatic event. The incidence of such injuries and the indications for surgery have increased during recent years. Graft repair and neurotization procedures play an important role in the treatment of patients with such injuries.

KEY WORDS: Brachial plexus, Nerve graft, Nerve trauma, Neurotization, Surgical approach

Neurosurgery 51:673-683, 2002 DOI: 10.1227/01.NEU.0000023600.59365.41 www.neurosurgery-online.com

In 1983, Kline and Judice (21) reported their 12-year experience in performing 171 consecutive operations on patients with brachial plexus (BP) injuries. One hundred thirty-nine BP lesions were traumatic, and the remainder comprised tumor and postirradiation cases. The authors stressed several important points in the management of BP trauma, such as the necessity to categorize each BP element as completely or incompletely injured, the indications and optimal timing for surgery, and the use of intraoperative electrophysiology to make the best surgical decisions regarding lesions in continuity. The number of patients with BP injuries seems to have increased since the 1980s because of progress in lifesaving emergency measures and compulsory helmet use for motorcyclists (30). The incidence and the severity of lesions in the nerves and vessels of the shoulder area have increased during the past 10 years (30). The introduction of magnetic resonance imaging (MRI) in preoperative evaluation, several anesthesiological or technical operative refinements, and improvement in reassessment of nerve grafting and neurotization procedures prompted us to analyze the epidemiology, preoperative management, operative findings, and treatment of 100 consecutive patients with injuries to the BP. These patients had surgery during a 3.5-year period. The postoperative follow-up period was 3 years or longer for 78 patients.

PATIENTS AND METHODS

Charts were reviewed for 99 consecutive patients with 100 traumatic BP injuries who underwent surgery performed by the senior author (DGK) between 1992 and 1995. Data collected included the age and sex of the patient, the mechanism of injury, associated injuries, preoperative neurological status, and the results of preoperative electrophysiological and radiological studies. Also noted were the time interval between trauma and operation; the surgical approach used; intraoperative findings of avulsion, rupture, scar, or compression of each exposed element; the intraoperative electrophysiological studies obtained; the therapeutic procedures performed; and the postoperative results. We used the Louisiana State University Medical Center grading system for motor and sensory function as well as level of recovery (20). In brief, according to the Louisiana State University Medical Center grading system, individual muscle grades progress from 0 (no contraction) to 5 (movement against maximal resistance), and the pattern of muscles paralyzed or severely paretic at the time of presentation indicates the level of injury, such as C5–C6, C5–C7, and so forth. A patient with a lesion at the level of C5–C6 or in the upper trunk presents with loss involving the supraspinatus, infraspinatus, deltoid, latissimus dorsi, biceps-brachialis, brachioradialis, and supinator muscles. A C5–C7 or upper plus middle trunk lesion involves, in addition to the C5–C6 motor deficit, triceps loss and often some weakness in pronation. There may or may not be weakness or loss of wrist extension and finger and thumb extension. The Louisiana State University Medical Center grading system of results is discussed in detail elsewhere (20). Grade 3 or useful recovery means contraction of proximal muscles against some resistance and of distal muscles against at least gravity. For example, Grade 3 recovery for a C5–C6 or upper trunk injury indicates good supraspinatus contraction, trace evidence of contraction for deltoid, and good contraction of the biceps-brachialis. In cases in which a chart listed incomplete follow-up, we attempted to contact the patient, the patient's family, or the referring physician by telephone.

RESULTS

Epidemiology

The median age of the 80 male and 19 female patients was 27 years (range, 5–70 yr). The histogram of ages is shown in *Figure 1*. The mechanism of injury included 77 closed and 23 open injuries (*Table 1*). Car and motorcycle accidents accounted for almost half of the cases of trauma, whereas 15 patients sustained their injuries during recreational activity (all-terrain vehicles, snowmobiles, bicycles, or sporting events).

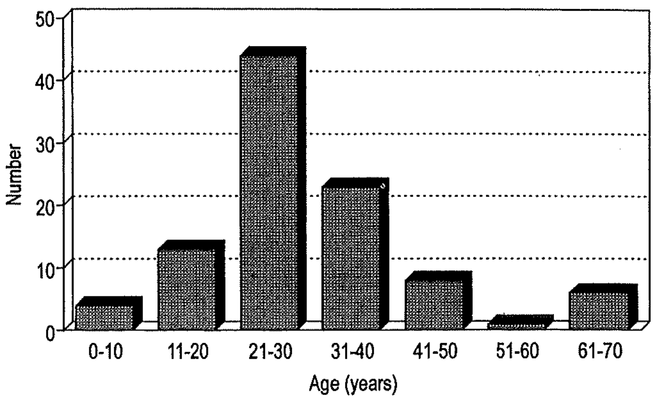

FIGURE 1. *Bar graph of the distribution of the patients' ages.*

Open injuries consisted of eight gunshot wounds. Nine injuries were attributable to operative iatrogenic trauma: infraclavicular (n = 1), supraclavicular (n = 5), or transaxillary (n = 1) biopsy of mass or resection, subclavian artery bypass (n = 1), and thoracoscopic sympathectomy (n = 1). Six were penetrating injuries: shard of glass (n = 1), grenade (n = 1), industrial accident (n = 1), metal impalement (n = 2), and stab wound (n = 1).

Associated major injuries (*Table 2*) were present in 59 patients with 42 long bone fractures, 10 spine fractures, 13 head injuries, and 13 chest injuries; 4 patients required a chest tube, and 2 patients underwent thoracotomy. Ipsilateral to the trau-

TABLE 1. Causes of brachial plexus injury

Mechanism	No. of patients
Closed injuries	
Motorcycle accident	27
Automobile accident	21
All-terrain vehicle accident	5
Pedestrian accident	5
Bicycle accident	4
Miscellaneous	4
Snowmobile accident	3
Sports-related accident	3
Object striking shoulder	3
Fall from height	2
Total	77
Open injuries	
Operative iatrogenic	9
Gunshot wound	8
Laceration	6
Total	23

TABLE 2. Major associated injuries in 59 patients with brachial plexus injuries

Injury	No. of patients
Upper-extremity fracture	27
Vascular tear or thrombosis	17
Lower-extremity fracture	15
Head injury	13
Chest injury	13
Spine fracture	10

matized BP were 23 fractures of the clavicle and 7 fractures of the first rib. Eighteen patients required an emergency operation in the neck region, mostly for repair of an injured vessel (*Table 3*).

Preoperative Clinical Status

The BP was traumatized on the right side in 55 patients and on the left side in 45 patients, including one patient with a bilateral BP palsy. At time of referral (average, 6.8 mo after injury), 39 patients presented with a flail arm, 19 with a C5–C6 injury, 15 with a C5–C7 injury, and 19 with a cord or cord-to-nerve level of injury (*Table 4*). Adverse prognostic factors, suggesting a very proximal level of injury (19), included Horner's sign in 29 patients and rhomboid, serratus anterior, and hemidiaphragm palsy in 0, 3, and 6 patients, respectively. Horner's sign (n = 29) proved to be a good predictive factor for T1 avulsion (n = 17; 59%) or for T1 neuroma (n = 8; 27%). Severe pain was present in 20 patients, including 14 patients with a stretch injury, 5 with open injuries (including one gunshot wound), and 1 patient with a BP injury sustained during a prolonged coma. BP injury was predominantly located at root level (n = 18) and was often complete (11 flail arms).

TABLE 3. Data regarding emergency neck operations performed in 18 patients with brachial plexus injuries

Characteristic	No. of patients
Trauma mechanism	
Open	10 (6 gunshot wounds)
Closed	8
Source of neurological deficit	
Panplexopathy	9
C5–C7	4
Infraclavicular (cord level)	5
Procedure	
Subclavian artery/vein repair	14
Carotid artery repair	1
Internal jugular vein repair	1
Neck hematoma evacuation	1
C6 spinal nerve suture	1

TABLE 4. Level of injury

Level	No. of patients
C5–C6	19
C5–C6–C7	15
C5–C6–C7–C8	2
C5–C7–C8–T1	1
C6–C7–C8–T1	1
C7–C8–T1	2
C8–T1	2
C5–C6–C7–C8–T1 (panplexopathy)	39
Cord or cord to nerve (infraclavicular)	19
Total	100

Other Preoperative Investigations

Fifty-seven patients underwent cervical myelography; computed tomographic scans also were obtained in six of these patients. Although MRI scans of the plexus were obtained in almost 40 patients, in only 7 patients was the MRI scan of sufficient quality that it could be used to assess nerve root injury. At least one root abnormality was recognized in 52 of these 64 examinations (*Table 5*). The preoperative predictive value of root status was 77% for myelography and 71% for MRI, although the latter was performed in a useful fashion in only a small cohort of patients.

Electrophysiological studies were obtained in 91 patients at Louisiana State University Medical Center at the time of referral. Needle electromyography usually confirmed that the clinically paralyzed muscles were completely denervated but also revealed early signs of reinnervation in some portions of plexus-innervated muscles, with a few nascent units in 21 cases. Sensory nerve conduction studies suggested a preganglionic level of injury of at least one root in 22 cases. Sampling of paraspinal muscles for denervation activity was also a useful adjunct in suggesting a proximal site for plexus injury. Preoperative electrophysiological studies correctly diagnosed 62% of recovering BP elements and 58% of preganglionically injured roots.

Surgical Approach

After a median interval of 7 months (*Fig. 2*), the 99 patients, each of whom had complete deficits in the distribution of at least one plexus element, underwent surgery in which an anterior (n = 96) or a posterior (n = 4) approach was used

TABLE 5. Radiological studies on stretch injuries[a]

At operation	Myelography (n = 57)		MRI (n = 7)[b]	
	Normal roots (n = 7)	Abnormal roots (n = 50)	Normal roots (n = 4)	Abnormal roots (n = 3)
No avulsion	5	11	3	1
Avulsion	1[c]	35	1	2
Not known	1	4	0	0

[a] MRI, magnetic resonance imaging.
[b] Forty-two of 100 patients had plexus MRI scans, but only 7 were usable in assessing nerve roots and whether they might be avulsed.
[c] Poor contrast filling on myelogram.

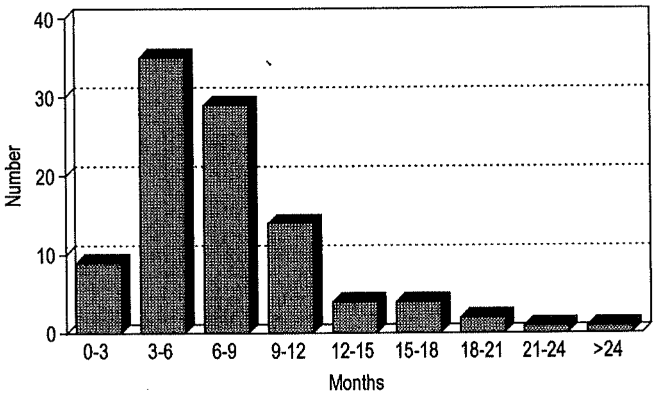

FIGURE 2. *Bar graph illustrating intervals between trauma and operation.*

(*Table 6*). Anterior approaches consisted of supraclavicular, infraclavicular, or supraclavicular plus infraclavicular procedures in 5, 14, and 77 patients, respectively. The posterior subscapular approach was chosen in four patients because of proximal lower root involvement and/or the presence of heavy scar anteriorly (11), as follows. One patient had a C8–T1 loss secondary to a thoracoscopic sympathectomy, another had undergone a prior C6 suture after a penetrating blunt force injury, a third had a gunshot injury that required prior vascular repair, and the fourth had a C7–T1 loss secondary to stretch injury caused by an automobile accident.

TABLE 6. Surgical approaches and operative procedures[a]

Surgery	No. of patients
Approach	
Anterior supraclavicular	5
Anterior infraclavicular	14
Anterior combined	77
Posterior subscapular	4
Procedure	
Neurolysis only	12
Direct brachial plexus reconstruction	
End-to-end suture	5
Nerve grafting	36
Direct BP reconstruction and neurotization	39
Neurotization only	8

[a] BP, brachial plexus.

Operative Findings

Root Avulsion

Root avulsion was diagnosed when the root appeared lax and displaced in a distal direction, leaving an emptied foramen. Electrophysiological studies were helpful when a root suspected to be avulsed remained in continuity within the foramen. In 38 patients, one or more roots were found to be avulsed. As shown in *Table 7*, 6 C5, 21 C6, 32 C7, 21 C8, and 18 T1 nerve roots were avulsed. In two patients, all five roots of the BP were avulsed.

BP Element Rupture

Discontinuity was a less frequent finding than root avulsion. It was present in more distal plexus in five upper and three middle trunks and in two divisions and three cords.

Scarred Elements

Scar was the predominant operative finding, and it was usually extensive. In most cases, the scar was associated with a neuroma in continuity at root, trunk, division, and/or cord levels (scar and/or neuroma) (*Table 7*). Less frequently, the scarred elements were found to remain in continuity but were attenuated (scar and/or atrophy). In one case, there was heavy scarring involving the lower two roots and several trunks. The injury was further complicated by compression from a calloused clavicle. Among the 20 patients who presented with severe pain, 8 had avulsion injuries and 12 had heavy scars and neuromas in continuity.

Operative Electrophysiology

Nerve action potentials (NAPs) were recorded in all patients. The mean number of NAP recordings obtained per patient was seven. The data permitted a rational decision for the elements that were scarred but still in continuity. Neurolysis was judged to be sufficient as the sole procedure in 12

TABLE 7. Operative findings for each brachial plexus element (100 brachial plexuses)

Location	No. of patients				
	Avulsion	Rupture	Scar/neuroma in continuity	Scar/atrophy in continuity	Scar/compression (clavicular fracture)
Roots					
C5	6	1	43	6	
C6	21	1	34	3	
C7	32	2	16	1	
C8	21		15		1
T1	18		14	1	1
Trunks					
Upper		5	31	2	1
Middle		3	15	1	1
Lower			16		1
Divisions		2	20		
Cords		3	30		
Total elements	98	17	234	14	5

patients with lesions that were scarred, in continuity, and conducted electricity. High-amplitude, fast-conducting NAPs were recorded in 19 roots, suggesting a preganglionic level of injury. The other NAP recordings were flat, indicating the need for resection of the damaged elements. Cortical evoked potentials were not used in this series.

Operative Procedures

Dissection of the traumatized BP implied external neurolysis in all cases. Neurolysis alone was performed in 12 patients because all elements were found in continuity and also transmitted a NAP. End-to-end suturing was possible for five BP elements, which were at the level of C6 (n = 1), T1 to lower trunk (n = 1), or medial cord to proximal ulnar nerve (n = 3).

Neurotization alone (n = 8) or combined with direct graft repair of the plexus (n = 39) was performed using the C3–C4 input to descending cervical plexus (n = 46), medial pectoral nerve (n = 3), accessory branch to sternocleidomastoid (n = 4), subscapular branch (n = 1), or phrenic nerve (n = 1). C3–C4 and descending cervical plexus were directed to one or more of the following: upper trunk (n = 22), suprascapular nerve (n = 9), middle trunk (n = 7), lateral cord (n = 18), or posterior cord (n = 11).

Nerve grafts were performed in 81 patients. The grafts were harvested from one (n = 56) or both (n = 22) sural nerves, antebrachial cutaneous nerve (n = 10), medial cord (n = 1), and/or phrenic nerve (n = 1). One to 15 nerve grafts, 1 to 6 inches long, were interposed between the BP elements. Proximal sites of suture of the grafts are shown in *Table 8*. The mean number and length of nerve grafts were 6.8 grafts per patient and 2.4 inches in length. The operation was extensive in most cases. The mean blood loss was 682 ml (range, 100–5000 ml). The pleura was entered and repaired in seven cases. Surgery lasted for as long as 9 hours; the mean surgical time was approximately 6 hours.

TABLE 8. Brachial plexus reconstruction using nerve grafts: Proximal line of suture (81 patients)

Location	No. of patients
Brachial plexus elements	
C5 spinal nerve	56
C6 spinal nerve	35
C7 spinal nerve	18
C8 spinal nerve	7
T1 spinal nerve	5
Upper trunk	2
Middle trunk	1
Posterior cord	5
Lateral cord	6
Medial cord	2
Extraplexus elements	
C4 spinal nerve	2
Descending cervical plexus	44
Medial pectoral nerve	3
Accessory nerve	4
Subscapular nerve	1
Phrenic nerve	1

Postoperative Results

At least 3 years of postoperative follow-up data were available for 78 patients. Two patients died, at 12 and 14 months

TABLE 9. Number of patients recovering to Grade 3 or better level after brachial plexus trauma and reconstruction (≥ 3 yr of follow-up)

Injury and procedure	No. of patients (%)				
Mechanism of injury					
Laceration					4 of 5 (80%)
Operative iatrogenic					5 of 6 (83%)
Gunshot wound					5 of 7 (71%)
Stretch injury					35 of 60 (58%)
Level of injury and type of operative procedure	C5–C6	C5–C7	C5–T1	Cord/nerve	Total
Neurolysis only	2 of 3	0 of 0	2 of 3	5 of 5	9 of 11 (82%)
Nerve suture	0 of 0	0 of 0	0 of 0	1 of 3	1 of 3 (33%)
Nerve grafting with or without neurotization	10 of 10	7 of 12	10 of 24	7 of 10	34 of 56 (61%)
Neurotization alone	1 of 2	0 of 0	1 of 3	0 of 0	2 of 5 (40%)
	13 of 15 (87%)	7 of 12 (58%)	13 of 30 (43%)	13 of 18 (72%)	

postoperatively; the latter committed suicide. *Table 9* summarizes the percentage of patients who had recovered useful function (i.e., to Grade 3 or better) after 3 or more years of follow-up, according to the mechanism of injury, the level of injury, and the type of operative procedure performed. Among the patients with open wounds, 14 (78%) of 18 patients experienced a Grade 3 or better recovery, as did 35 (58%) of the 60 patients with stretch injuries. Among the patients with C5–C6 or C5–C7 lesions that were repaired by nerve grafting, 10 (91%) of the 12 patients who had surgery within 6 months of injury recovered to at least Grade 3 level, whereas 8 (62%) of 13 patients experienced Grade 3 or better recoveries after surgery performed later than 6 months after injury. *Figure 3* shows the outcome data of these 25 patients with regard to the timing of surgery.

Recovery was better among patients with C5–C6 palsy or cord and/or nerve level of injury than among patients with C5–C7 or C5–T1 palsy (87, 72, 58, and 43%, respectively, of patients with Grades 3 or better recovery). Concerning the type of operative procedure performed, the best result was obtained after neurolysis (9 of 11 patients with Grade 3 or better). Neurotization as an isolated procedure led to useful arm function in two (40%) of five patients. Neurotization with the use of descending cervical plexus nerves associated with direct BP repair led to good recoveries in 12 (40%) of 30 patients at the 3-year follow-up examination. Medial pectoral nerve transfer gave a correct recovery in two (67%) of three patients. This transfer procedure is being considered as a secondary procedure in four other cases (*Table 10*). Postoperative follow-up was available for 14 patients with severe pain preoperatively: pain was absent in three patients, well reduced in five patients, and severe in six patients. Among the six patients with severe postoperative pain, dorsal root entry zone lesions were created in one patient and were being considered in another (*Table 10*). Data regarding employment status were available for 52 patients: 28 are employed, 2 are retired, 11 are students, and 11 are considered permanently disabled. With regard to self-reported quality of life, 6 patients described it as very good, 12 patients as good, and 17 patients as satisfactory.

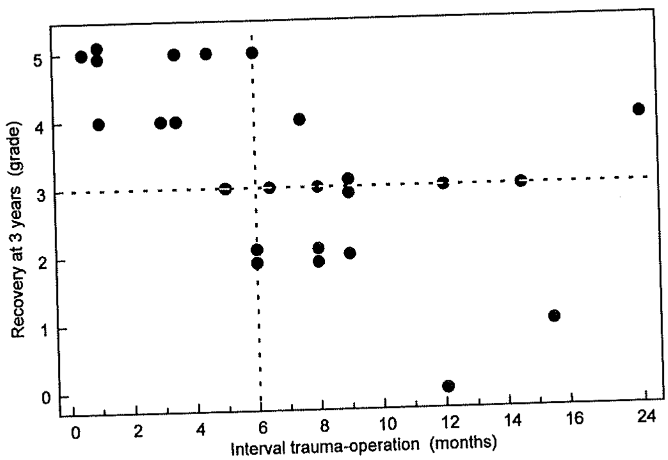

FIGURE 3. *Scatterplot of postoperative outcomes at 3-year follow-up in 25 patients with C5–C6 or C5–C7 stretch injuries that were repaired by nerve grafting, according to timing of surgery.*

DISCUSSION

The previous published series of patients with BP lesions who were treated by the senior author (DGK) (21) included cases of tumor and plexitis as well as traumatic lesions. In the present series, we focused our attention on patients with BP trauma. This article reviews the management of a series of more recent cases to determine whether treatment recommendations have changed. The present series (1992–1995) is compared with the previous series (1968–1980) in *Table 11*, which shows a fourfold increase in the number of stretch lesions treated surgically, whereas the incidence of open injuries (lacerations and gunshot wounds) for which surgery was per-

TABLE 10. Secondary procedures

Procedure	Performed	Considered
Nerve repair		
Neurotization medial pectoral nerve → musculocutaneous nerve	1	4
Idem + neurotization Cranial Nerve XI → suprascapular nerve		1
Reconstructive procedures		
Tendon transfers	1	1
Shoulder fusion	1	
Ablative procedures		
Amputation below shoulder	1	1
Amputation below elbow	0	3
Pain procedures		
Drezotomy	1	1

TABLE 11. Number of patients with traumatic brachial plexus lesions who underwent surgery and time from trauma to operation in two different series at Louisiana State University Medical Center

Mechanism of trauma	1968–1980 series	1992–1995 series
Laceration	n = 33 (24%); 2.7 mo	n = 15 (15%); 3.7 mo
Gunshot wound	n = 46 (33%); 19 wk	n = 8 (8%); 29.2 wk
Stretch	n = 60 (43%); 23.8 wk	n = 77 (77%); 39.2 wk

formed remained fairly stable. These findings suggest an increase in the incidence of, the number of referrals for, and/or the operative indications for closed BP injuries.

Epidemiology and Clinical Presentation

Epidemiological data from the present series are in accordance with those reported by others (13, 25, 26, 32, 33, 35, 36). In our study, 81% of the patients were male, 61% were younger than 30 years of age, 59% were multitraumatized, and the most common patterns of injury were panplexopathy (C5–T1) (39%), C5–C6 (19%), C5–C7 (15%), and cord or cord-to-nerve level (19%). The right BP was involved in 55 patients, and the left was involved in 45 patients. Bilateral BP palsy has been reported rarely in obstetrical cases (16), and fortunately it is extremely rare when the mechanism is stretch caused by a vehicular accident. Included in this series is a 19-year-old man who had right C5–T1 palsy and left C5–C7 palsy as a result of a motorcycle accident. He also had chest trauma, a right subclavian artery injury requiring operative reconstruction, a C7 facet fracture, and a fracture of the right femur and radius. He underwent an operation on the left BP with nerve grafting and neurotization procedures at 14.5 months after injury, as well as an operation on the right BP with extensive neurolysis at 20.5 months postinjury.

Preoperative Management

In these patients, conducting a thorough preoperative investigation is of prime importance. Operative indications and contraindications are based on clinical data combined with electrophysiological and radiological findings (19, 24). With the use of peripheral and paraspinal musculature electromyography as well as sensory nerve conduction studies, the electrophysiological workup provides important information regarding preganglionically injured or recovering BP elements. The current opinion concerning imaging studies is that myelography should be performed 1 or 2 months after injury when BP palsy persists. Six types of myelographic findings in patients with BP injury have been described, from normal nerve root sleeves to the presence of one or more large pseudomeningoceles (29). The latter usually indicate root avulsion, with a known false-positive and false-negative rate of approximately 10%, although a false-negative rate of 32% occurred in the Mehta et al. (25) series.

We obtained correct information regarding nerve root status with the use of myelography in 77% of our cases. By allowing good visualization of anterior and posterior rootlets, performing computed tomographic myelography led to correct diagnoses in 85% of the cases in the series reported by Carvalho et al. (8). MRI has not supplanted cervical myelography, although it seems to hold future promise (31, 37). A "false meningocele" can be observed on the T2-weighted sequence of the MRI examination displayed in *Figure 4*. In some cases, however, high-resolution MRI can reveal anterior and posterior rootlets as distinctly as computed tomographic myelography. Furthermore, in theory, MRI can study not only the proximal BP at root level but also the more distal BP, as Gupta et al. (14) demonstrated. Lateral or end neuromas and diffuse or focal fibrosis can be suggested by conducting a thorough examination in approximately 110 minutes.

Indications and Timing for Surgery

Indications for surgery are well established, as are contraindications, which are usually but not always relative (10, 19, 24). An exception is the patient who is not selected for surgery because of multiple avulsions demonstrated in preoperative investigations. The reasons for this evolving concept are as follows: 1) the definite diagnosis of root avulsion may need operative confirmation, 2) partial avulsion sometimes permits partial repair of the involved root, and 3) neurotization (i.e., nerve transfer) procedures can reinnervate some portions of the distal plexus.

The timing of the operation for closed and open injuries is different. Emergency surgery is required most often for vascular reasons. Lacerating injuries should be explored either acutely, if the mechanism is sharp, or within 2 to 3 weeks if the injury is a blunt. Gunshot wounds without concomitant vascular or thoracic injury should be managed conservatively initially, because they usually leave the nerves in continuity; gunshot wounds are explored at 2 to 4 months after injury if no recovery occurs in the distribution of elements that can be helped by repair. Closed traction injuries are best operated at 4 to 5 months after injury. Most authors agree with these recommendations; yet, most patients in these authors' and our own series had surgery later usually because of delayed referral (13, 17, 21, 24). As shown in *Table 11*, in the present series, gunshot wounds were explored at an average of 7 months (29.2 wk) postinjury, and stretch injuries were explored at an average of 9 months (39.2 wk) after trauma. This finding is in part the result of delayed referral to a specialized center. Other patients underwent late operations either because they had severe, multiple trauma injuries initially or for a severe pain syndrome.

FIGURE 4. *T2-weighted MRI scans. Anteroposterior (A) and axial (B) views demonstrating a pseudomeningocele on the right C8 nerve root.*

Magalon et al. (22) differed greatly from other authors with regard to their timing of surgery. They stated that exploration should be performed within 7 days after injury because it is easier and because relatively short grafts can be used. We think that early surgical exploration exposes a portion of patients with BP injury to a needless operation; furthermore, operation for closed injuries is best performed at a time when intraoperative NAP recordings can confirm the need for resection or neurolysis of a neuroma in continuity (21). In a previous study involving gunshot wounds, 48 of 166 plexus elements with complete clinical and electromyographic loss were spared resection or had a split repair on the basis of NAP recordings (18).

Operative Management

The first aim of surgery is to explore the BP and determine the anatomic extent of the lesions. We question the need of hemilaminectomy for intradural inspection of nerve roots (8); in our opinion, preoperative imaging studies and pre- and intraoperative electrophysiological studies provide enough information regarding the presence or the absence of nerve root avulsion, especially when combined with serial sectioning of the spinal nerves while searching for fascicular structure. The technique of reimplanting ventral roots into the spinal cord demonstrated promising results in a recently published clinical series (7), although further follow-up seems necessary for that small series. In theory, motor axons should be able to regenerate after a preganglionic injury has been repaired. The majority of the BP lesions in our series were approached by an anterior, usually both supra- and infraclavicular, route. Exposure of the plexus either above or below the clavicle or very proximally by a posterior approach (11) was performed in selected cases.

We found 38% of the patients (49% of those with a closed injury) to have one or more roots avulsed. Avulsion of four or all five roots was found in only six cases, in contrast to 24% in the Alnot (2) series and 30% in the Narakas (30) series. The importance of intraoperative NAP recordings is reemphasized by the 12% rate of neurolysis on the basis of positive recordings in our series: neuromatous BP elements that were in continuity were dissected free of scar but otherwise were left alone because they conducted a NAP. We do not favor internal neurolysis as a primary method of treatment as others do (25), but sometimes we perform it when a split repair is indicated.

In 81% of our patients, we repaired all or some portion of the BP found transected, or more likely after the resection of a nonconducting neuroma, usually with the use of sural grafts. In slightly more than half of the cases, enough proximal stumps were available in the BP to place grafts to more distal elements. The majority of grafts were sutured proximally at the intraforaminal levels of the C5 and C6 spinal nerves. In some cases, this procedure necessitated a very proximal exposure of the spinal nerve, and sometimes of the root, by drilling or rongeuring away part of the facet to reach a useful fascicular structure.

Most surgeons who treat patients with BP injuries attempt to reconstruct the plexus, even in patients with severe damage sustained to elements over a great length or with total or near-total avulsion (1, 3, 5, 15, 17, 22, 28). This treatment in these patients implies the use of long grafts and/or neurotization procedures. Both sural nerves frequently are used (2), with the grafts being as long as 6 inches, or 22 cm, in the series reported by Kanaya et al. (17), whereas the number of grafts varied from 1 to 15 in other series (2, 15, 17).

We and others favor performing neurotization with the use of regional nerves such as C3–C4, descending cervical plexus, or accessory as donors (1, 2, 4, 12, 33, 34, 38). The anatomic proximity of the accessory or descending cervical plexus is advantageous, in some cases allowing direct suture to a BP distal element such as the suprascapular nerve. The use of C3 and/or C4 anterior rami coaptation to trunk level, which was reassessed by Yamada et al. (39), is sometimes a useful adjunct procedure. Conversely, the more complex procedure of intercostal neurotization can restore some biceps function in approximately 50 to 65% of cases, but it seldom restores other useful functions (23, 28). In recent years, for C5–C6 and C5–C7 avulsions in which C8–T1 and thus hand function were intact, we increasingly have used the medial pectoral (i.e., C8–T1) branches for transfer to musculocutaneous nerve. The accessory (i.e., the XIth cranial nerve) also is used to neurotize the suprascapular nerve. We have not used the technique of sacrificing the contralateral healthy C7 spinal nerve to reinnervate the lesioned plexus (6). Although the incidence of loss to the donor limb is small, we have been loath to jeopardize the intact arm in any manner, because the recipient limb is, of course, already severely disabled.

The decision regarding the best repair procedures is made when the BP is exposed and after electrophysiological examinations have been performed. The limiting factor for BP reconstruction usually lies at the root level. The possibilities of reconstruction of the distal plexus depend mainly on how many proximal nerves are available to connect the motor and sensory units of the spinal cord and ganglion to the distal BP. We favor direct intraplexal repair when enough roots are available proximally; if necessary, we expose the nerve root very proximally, at the intraforaminal level. In our experience, direct repair of nerve elements provides better results than neurotization procedures, which we use as a second choice when insufficient proximal roots are available. For example, if the C5 root is found avulsed or scarred to the intraforaminal level, usually we use a spinal accessory nerve to repair the suprascapular nerve. BP reconstructive surgery is both complex and extensive. One must be prepared for heavy scarring, subclavian or axillary vascular injury, entrance through pleura, severe blood loss, and the need for long segments of graft material. Furthermore, management of BP injury requires a multidisciplinary team, and, in selected cases, secondary procedures are performed to increase the functioning of the arm.

Operative Outcome

The surgical results in this series are in accordance with those reported by other investigators (1, 2, 3, 5, 15, 17, 20, 25, 27, 32, 35). Patients with open injuries have better outcomes than do those with stretch injuries. Regarding supraclavicular lesions, patients with repaired C5–C6 lesions fare better than patients with other patterns of spinal nerve injuries. Patients with cord or cord-to-nerve injuries frequently recover useful arm function. Isolated neurolysis of BP-conducting elements yields good results in a high percentage of cases; furthermore, neurolysis permits the reduction or the disappearance of pain in 57% of patients. BP reconstruction with the use of grafting procedures leads to a satisfactory result in 61% of patients, and neurotization or nerve transfer is successful in 40% of patients. Thus, such operative repair techniques seem to play an important role in BP reconstruction and allow many patients to recover the use of an arm. Only 22% of patients become totally and permanently disabled after BP trauma and operative reconstruction, whereas most patients think that their quality of life is at least satisfactory (9).

CONCLUSIONS

Our study demonstrates that the epidemiology of BP trauma has not changed substantially during the past 20 years. Most such injuries still occur in young people as a result of traffic accidents, especially accidents involving motorcycles. The incidence of traction injuries has increased, however, as perhaps has the number of patients who can undergo surgery because of surgical advances. The current trend is toward attempting surgical reconstruction either by direct repair and/or by nerve transfer, even when multiple roots or spinal nerves exhibit evidence of proximal injury. Future improvement in the resolution of MRI may prove to be effective enough to evaluate the physical continuity of nerve roots and spinal nerves, and MRI may replace cervical myelography. BP injury management remains challenging and suggests the need for early referral to a specialized center. Graft repair and neurotization procedures play an important role in BP reconstruction. Follow-up of the patients in this series confirms the premise that an aggressive surgical approach, combined with the use of these therapeutic modalities, remains appropriate.

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Acknowledgment

We thank Judith Hickey, R.N., Department of Neurosurgery, Louisiana State University Medical Center, New Orleans, LA.

COMMENTS

This report is written by a respected senior author (DGK) with extensive experience in the management of peripheral nerve trauma. The principles described should be of interest to many neurosurgeons. They reinforce the management paradigm that the authors have advocated for the treatment of other peripheral nerve injuries. The analysis is thorough and methodical. Its conclusions may be limited by the heterogeneity of the patient population in terms of mechanism, operative findings, and the treatments administered. The volume of brachial plexus (BP) injuries described in this article will be difficult to replicate, however, and these guidelines approach authoritative status on that account alone.

Arun Paul Amar
J. Peter Gruen
Los Angeles, California

Surgical series by leaders in a particular field can serve as a benchmark with which to assess one's surgical results and to allow clinicians to inform patients regarding the potential benefits of a particular surgical procedure. This article describes the surgical treatments administered to and the clinical outcomes of 99 patients who underwent 100 consecutive operations for the treatment of traumatic BP injuries. All operations were performed by Dr. Kline, a pioneer and living legend in this field, during a 3.5-year period. Postoperative follow-up examinations were conducted for at least 3 years in at least 78 of the patients. Clinical outcome information is readily available in the text and tables of the article. This article is a follow-up to a previous article by Kline and Judice (1), in which they reviewed their 12-year surgical experience in 171 BP cases involving trauma, tumor, or postirradiation abnormality.

This article contains many interesting observations. Of the 100 BP injuries, 77 were closed and 23 were open. A total of 59 patients had associated injuries. Preoperative electrophysiological studies led to correct diagnoses in 62% of patients with recovering BP elements and 58% of patients with roots that were preganglionically injured. The great majority of damaged BP elements exhibited extensive scar formation; 13 plexus elements ruptured and revealed discontinuity, and 38 patients had one or more avulsed spinal nerve roots. Clinical outcome was defined as good if a Louisiana State University Medical Center Grade 3 or better was achieved, which is defined as voluntary contraction of proximal upper-extremity muscles against some resistance and contraction of distal muscles at least against gravity. A good outcome occurred in 9 (81%) of 11 patients who underwent only surgical neurolysis. Isolated neurotization produced useful arm function in two (40%) of five patients and in two (67%) of three patients who underwent medial pectoral nerve transfer to the musculocutaneous nerve. Neurotization using descending cervical plexus elements combined with direct BP repair produced good outcomes in 12 (40%) of 30 patients. Of 18 patients with open wounds, 14 (78%) had good outcomes, and 35 (58%) of 60 patients with stretch injuries had good outcomes. All 10 patients with C5–C6 stretch injuries repaired by nerve grafting recovered useful arm function. Of 14 patients who presented with severe preoperative pain, the pain was absent after surgery in 3 patients (21%), well reduced in 5 (36%), and unchanged in 6 (43%).

I next summarize a few of the most important messages to take away from this article: it is critical to perform a careful and thorough preoperative and intraoperative assessment of damaged BP elements. Functioning nerve elements should be neurolyzed and left alone. Direct intraplexal repair of damaged plexus elements, if possible, affords the patient a better outcome than does neurotization. Neurotization of the musculocutaneous nerve with the medial pectoral nerve shows promise when indicated. Patients who undergo surgical repair of open injuries fare better than those with closed stretch injuries. Patients with C5–C6 repaired stretch injuries fare better than those with other types of proximal spinal nerve injuries. Operative repair within 6 months of the traumatic injury is more effective than later repair. This benchmark article sets a standard for which all peripheral nerve surgeons may aim.

Michel Kliot
Seattle, Washington

1. Kline DG, Judice DJ: Operative management of selected brachial plexus lesions. **J Neurosurg** 58:631–649, 1983.

This article by Dubuisson and Kline is a clear formulation of the complex problems involved in treating patients with BP injuries. Many consider this topic difficult to analyze. Narakas (1) summarized several thousand cases of BP injuries and concluded that, in general, the results of surgery performed to treat patients with BP injuries are disappointing, although some patients have had favorable results. These authors change that view of BP surgery from pessimistic to cautiously optimistic. This article includes precise grading of BP injuries related to neurological findings and grouping of open and closed injuries; direct versus stretch injuries; diagnostic studies including computed tomographic myelography, magnetic resonance imaging, and electrophysiological studies; and surgical indications, techniques, and results. The discussion is accurate, precise, and detailed.

The authors express considerable flexibility in selecting patients for surgery and in the timing of surgery. Not only peripheral nerve surgeons but also general neurosurgeons must be acquainted with these diagnostic and therapeutic measures as a standard for neurosurgical practice. Neurosurgeons must encourage other specialists to send patients with BP injuries to surgeons who are experienced in performing BP operations.

In some patients with closed BP injuries, spontaneous recovery occurs because the loss of function is caused by only a temporary interruption of nerve conduction (neurapraxia) as a result of axon loss for a short distance with preservation of the myelin sheaths (axonotmesis) or total but short interruption of the axons and nerve sheaths (neurotmesis). Because of the possibility of spontaneous recovery in these cases, 4 months of observation is appropriate.

Peripheral nerve regrowth is 1 mm/d. Unfortunately, this rule is strict. The distance from the shoulder joint to the wrist joint in a patient who is 6 feet tall is 60 cm, whereas the length of the same segment in an infant is 20 cm. In adults, early spontaneous or surgical reconnection of the severed nerve restores only the muscles in the arm segment across one joint. In contrast, an infant in our series (2) with C8–T1 root avulsion who underwent C4 anterior ramus-lower trunk coaptation regained small hand muscle recovery (after publication of the series in *Neurosurgery*, at which time only voluntary motor units appeared in the those muscles). In cases of nerve root avulsion, coaptation should be performed as soon as neuronal interruption proximal to the sensory ganglion is confirmed by the combination of computed tomographic myelography, electromyography, and sensory conduction studies, ideally within 3 weeks after injury.

I am pleased to learn that Dr. Kline's group adopted the use of C3 and C4 anterior rami as the donor for bypass coaptation in cervical nerve root (C5–C7) avulsion. Functional recovery is much more extensive with the use of such a procedure than with the use of single-nerve neurotization.

Shokei Yamada
Loma Linda, California

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